LESSONS FROM THE XB-70 AS APPLIED TO THE SUPERSONIC TRANSPORT

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INTRODUCTION

The lessons from the XB-70A program that have been selected for discussion are only a few of the things that have been learned during the program. These things will certainly apply to the supersonic transport (SST). In some cases they will apply to any large airplane, and in a few cases they will apply to almost any airplane. The XB-70 is a very valuable research airplane; there is no other airplane in the world of similar size that can fly in the same speed environment. Many of its design features were pushing the state of the art; therefore, both positive and negative results were obtained, providing validation or correlation of design prediction techniques. It also provided information on operational factors applicable to a large supersonic aircraft. The program has been expensive in money, time, and personal sacrifice, but if the knowledge gained from the XB-70A test program makes it possible to avoid even one catastrophic SST accident, the program will more than pay for itself.

DESCRIPTION OF AIRPLANE AND TEST PROGRAM

The XB-70A (fig. 1) is a large, delta-wing, supersonic airplane with dual vertical-tail surfaces, a movable canard surface with trailing-edge flaps, and a movable nose ramp to provide acceptable visibility at low speed and reduced drag at high speed. The airplane has retractable landing gear and wing tips that are folded downward to improve directional stability at transonic and supersonic speeds. It is 189 feet long with a wing span of 105 feet. The maximum taxi weight is 542,000 pounds, and the takeoff gross weight for most flights is approximately 532,000 pounds. The airplane is crewed by two pilots on experimental or research flights, which have been flown at speeds up to Mach 3.0 and altitudes above 70,000 feet.

The flight program began on September 21, 1964, under U. S. Air Force direction and funding. Since March 29, 1967, a joint NASA-USAF program has been directed and primarily funded by NASA. Flight support has been provided by the contractors, North American Rockwell and General Electric, since the beginning of the program.

The breakdown of flights and flight hours is shown in the following table:

	Airplane 1	Airplane 2	Both airplanes
Flights	78	46	124
Flight hours	149:13	92:22	241:35
Supersonic flight hours	55:41	47:17	102:58
Flight hours at Mach 2.0 or above	23:08	27:18	50:26
Flight hours at Mach 2.5 or above	5:55	16:34	22:29
Flight hours at Mach 3.0 or above	:02	1:46	1:48

The test programs covered many areas of interest. Some of the most significant are:

Stability and control
Airplane handling characteristics on the ground and in flight
Performance of airplane, engines, inlet, and systems
Structural loads on airplane and landing gear
Noise and sonic boom
Ground effects during takeoff and landing
Response to turbulence
Modal control and gust alleviation
Operational characteristics

DISCUSSION

Realism in Design and Operation

One of the most significant lessons from the XB-70 should be the need for conservative realism in designing and operating the SST. The XB-70 was originally conceived as having intercontinental range. The operational experience to date in conjunction with onboard recorded data indicates that the design range may have been missed by more than 25 percent; the reasons are many. Using the then best available methods of interpreting wind-tunnel data, the contractor along with some Air Force and NASA people overestimated the lift-to-drag ratio, underestimated the transonic drag, and overestimated the inlet performance that could be obtained under practical operational conditions. Also, there were necessary but unplanned increases in airplane empty weight. The result was a large reduction in performance.

Flight Characteristics Versus Wind-Tunnel Predictions

Although agreement between flight and predicted airplane stability and control characteristics was realized in most instances, some of the stability characteristics and handling qualities were unlike the wind-tunnel predictions. For example, the airplane exhibits excessive adverse yaw due to aileron input at all flight conditions, but this characteristic was not predicted for a large portion of the flight regime. Large sideslip angles can be inadvertently generated at some speeds, and the pilot may not be aware of them because under some conditions the transverse accelerations in the cockpit are low, making the pilot relatively insensitive to directional motions. Also, the airplane riding qualities are less than desirable under turbulent-air conditions. Much additional wind-tunnel testing has been done by NASA during the XB-70 test program in an attempt to correlate wind-tunnel data with the flight-test results. Some differences between the model and the airplane are the result of aeroelasticity. Other differences are due to scale effect. Correction factors validated during the test program have brought these data into closer agreement. Hopefully, as a result of these studies, there is now a better basis upon which to make predictions for the SST. Since it appears that the profit margin for the SST will not be high enough to afford large errors in predictions, even with improved methods of prediction it seems that some allowances must be made for minor miscalculations and for the unknown factors that always influence a new airplane.

Enroute Atmospheric Predictions

Another thing that is not new but has certainly been well illustrated is the need for accurate atmospheric predictions along the flight route and especially in the acceleration area. On the most recent XB-70 flight the temperature at the acceleration altitude was estimated to be 8° C to 10° C warmer than standard-day conditions. Inflight data and the performance obtained indicated that the temperature predictions were very close and the fuel usage was considerably higher than had been originally planned, using charts for standard-day conditions. Figure 2 shows the standard-day fuel-usage predictions versus the actual conditions for a segment of the flight. As can be seen, the fuel remaining was 14,000 pounds low at the northwest turning point and the speed was only Mach 2.40 instead of the predicted Mach 2.52. Temperatures warmer than those for a standard day are bad enough when known and accounted for as on this flight, but if they occur without being predicted, there is a good likelihood that fuel reserves will be dangerously low at the destination. In addition, turbulence has been encountered even at altitudes above 60,000 feet, and turbulence is a significant factor in reducing supersonic performance. The predictions of turbulence encounters have not been accurate on many flights.

Variable-Position Nose Ramp

The XB-70A nose ramp (fig. 3) can be operated at indicated airspeeds of up to 560 knots. This has been found to be extremely valuable. It provides the pilot an opportunity to have forward visibility and reduces the possibility of collision, therefore lessening anxiety during any subsonic operation and even during supersonic speeds. The airplane has been flown to speeds in excess of Mach 2.50 on numerous flights with the windshield ramp down (best visibility). There is a small performance penalty caused by the lower climb-speed schedule in this configuration, 560 KIAS versus the normal 575 KIAS, and by the increase in windshield drag. The improved view of the natural horizon with the nose ramp down is a big aid in flying the airplane and gives the pilot more time to devote to cockpit duties other than instrument flying. The capability of rapidly operating the XB-70A nose ramp up or down over most of the flight envelope is very desirable. It enables an occasional "quick look" when desired. Certainly some reduction in visibility is acceptable to obtain less drag and improved performance at high speed, but those who feel that forward visibility is completely unnecessary during acceleration and cruise are not in agreement with the XB-70 pilots.

Cockpit Instruments

The XB-70 has vertical-tape flight instruments and round-dial engine instruments. It would be nice to say that the XB-70 pilots have concluded that vertical-tape flight instruments are better than round-dial flight instruments; however, that is not the case. The pilots seem to be about evenly split in their preferences between tapes and round dials. I have flown tapes in simulators, an experimental F-102, C-141's, and the XB-70 and have flown round dials in B-52's, B-58's, F-104's, C-130's, and many other types of airplanes. A satisfactory job can be done with either type, but I prefer round dials, since trends are more easily recognized and possibly because of past experience and training. A feature of the XB-70 and some other airplanes is the digital readout of airspeed and altitude. This is extremely helpful in precise instrument flying. A digital readout of Mach number should also be provided. One of the very desirable engine instruments is an exhaust gas temperature (EGT) gage with a warning light on the face to call attention to an over-temperature condition. Early in the test program the EGT gages installed did not have this warning-light feature, and several engines had to be removed for inspection when pilots failed to immediately see an over-temperature condition. Since the installation of gages with warning lights, there have been numerous occasions of over-temperature alerts to the pilots. The gages have paid for themselves many times over. A yaw or sideslip instrument will probably be required as will a total temperature gage. If the design cruise speed causes the total temperature to always be near the limiting temperature, a warning light or bell will have to be provided. Prolonged exceeding of the limiting temperature is probably as critical as exceeding the limiting speed.

There have been several publicized statements to the effect that "it is very difficult to hold a constant altitude at high speeds in the XB-70." The airplane does not have an autopilot, and there is no question about it being more difficult to maintain altitude with the XB-70 than with a subsonic jet transport, because small angular changes in pitch attitude result in large rates of altitude change. At Mach 3.0 and 70,000 feet altitude, an attitude change of 1° causes the rate of climb to change approximately 3000 feet per minute. The difficulty in holding altitude is probably due in part to the longitudinal control system inasmuch as the trace of elevator force during a sonic-boom run (fig. 4) shows that a high frequency of small inputs was required by the pilot. The same figure also shows that altitude was being held relatively constant at Mach 2.51. The improved altitude holding capability was attributed primarily to installation of an attitude director indicator with a pitch scale of doubled sensitivity. The original instrument was difficult to read within 1/4°; whereas, a more sensitive instrument (fig. 5) provided greater resolution and ease of maintaining altitude. A cockpit modification (fig. 6) has been made recently to allow in-flight selection of attitude-indicator sensitivities ranging from 2:1 (2° on the instrument versus 1° outside) up to 5:1. Only a few flights have been flown with the modified instrument, but preliminary results indicate that a selection in the sensitivity range between 3:1 and 4:1 will probably be more satisfactory for high-speed flying. The attitude director indicator (fig. 5) also has a 10:1 vertical pitch scale to the left of the attitude ball, but that appears to be oversensitive.

Overspeed Operation

The problem of overspeeds deserves serious consideration. To obtain optimum performance, most supersonic airplanes will need to operate near maximum placard speeds during the climb, cruise, and descent. The XB-70 is normally accelerated to and then climbed at 560 KIAS (nose ramp down) or 575 KIAS (nose ramp up). The pilot is faced with the task of keeping the speed near maximum placard to improve performance, but not above placard because of design considerations. The planned climb schedule has been inadvertently exceeded from 5 to 10 knots indicated airspeed on a number of XB-70 flights. Although deviations are small, it is virtually impossible to hold an exact climb schedule. The most frequent excursions occur at the completion of the constant-altitude transonic acceleration and during the initial transition to a constant indicated airspeed climb schedule. Most pilots begin a gradual pullup to phase into the climb when 15 to 20 KIAS below the desired climb speed, but overspeeds still sometimes occur. No warning device is installed on the XB-70, but for an SST it seems that the warning bell or light should be set at least 10 to 15 KIAS and Mach 0.05 below the placard limit speeds or the maximum speed will be exceeded and cause the warning to be triggered on numerous flights.

Inlet Operation

The XB-70 uses a system of movable inlet panels and airflow bypass doors to control the air being supplied to the engines. These inlet panels and bypass doors provide a means of bringing the normal shock wave inside the inlet at speeds above Mach 2.0 to improve inlet efficiency. With the normal shock inside the inlet, it is considered to be "started;" when the normal shock moved outside the inlet, it is considered to be "unstarted." The normal shock position is sensitive to speed, angle of attack, sideslip, and engine speed. The method of controlling the shock position with the XB-70 is semiautomatic and the switches, controls, and gages (figs. 7 and 8) require much attention from the copilot. When an inlet "unstart" occurs, the XB-70 experiences airframe buffet which ranges from light at Mach 2.2 to heavy at speeds above Mach 2.7. Sometimes the airframe buffet is accompanied by engine stalls and/or possible inlet buzz. Many "unstarts" have been experienced during the test program. Some were planned and others were unintentional. It usually takes from 5 to 10 seconds for the copilot to "restart" the inlet; therefore, the flight crew endures the buffet for a short time. The paying passenger is not likely to willingly endure that type of buffet more than once. The SST inlet control and inlet "restarting" systems must be reliable, automatic, and very fast in returning an inlet to normal operation after an "unstart."

Flying Qualities

The XB-70 has some undesirable flying qualities, such as the yaw due to aileron, development of excess yaw under certain conditions, and the negative dihedral effect at high speeds, but the airplane has excellent longitudinal and directional restoring characteristics. Turning off the augmentation (dampers) results in a deterioration of flying qualities; however, the system can be safely turned off in any flight regime. All takeoffs and landings on the early flights were made with the augmentation off. Intentional sideslips, releases from sideslips, pitch pulses, and wind-up turn stability maneuvers have been routinely accomplished at speeds as high as Mach 2.90 with all the augmentation off. On several recent flights, after the pitch augmentation was turned off, the airplane was flown "hands off" during phugoid tests for periods of over 5 minutes at Mach 2.50 and approximately 62,000 feet. The pilot controlled minor banking tendencies through the rudder pedals, with left rudder to command right rolls and right rudder to command left rolls because of the negative dihedral effect at that speed. Using reasonable pilot effort, the SST should be capable of flight with all augmentation off throughout its entire speed envelope.

Deceleration and Descent

The importance of proper planning and execution of the deceleration and descent from high-speed cruise should not be underestimated. The slowdown and descent from a Mach 2.70 cruise flight will start 200 nautical miles or more from the destination in order to become subsonic at the proper distance and altitude to allow integration with the subsonic jet traffic. Receipt of the traffic clearance and the initiation of the slowdown and descent cannot be delayed. With a speed of approximately 27 nautical miles per minute, the pilot does not have the opportunity to "standby" while awaiting the clearance. He should have that clearance well before reaching the deceleration point. The flight path must be flown in a manner to minimize sonic booms, which means that the speed will probably be at Mach 1.10 or below by the time an altitude of 35,000 feet is reached. I flew a fairly typical deceleration and descent in the XB-70 during a 59-minute flight from Edwards AFB, California, to Carswell AFB, Texas. The slowdown started from Mach 2.70 at 64,000 feet altitude over Lubbock, Texas, and the airplane arrived over Carswell AFB at 5,000 feet above the ground. The sequence of events for the flight was as follows:

Time to Carswell, minutes	Speed	Altitude, feet	Remarks
:16	2.70 Mach	64,000	Lubbock, Texas - 238 n. mi. to Carswell AFB. Thrust reduced from afterburner to military power.
:12	2.00 Mach	50,000	Decelerating and descending.
:09	1.50 Mach		Decelerating and descending 90 n. mi. from Carswell AFB.
:08	1.40 Mach		Thrust reduced below military power.
:05.5	1.00 Mach	30,000	Decelerating and descending 50 n. mi. from Carswell AFB.
:02.5	.90 Mach	20,000	Descending. 25 n. mi. from Carswell AFB.
:00	400 KIAS	5,000	Over Carswell AFB.

The XB-70 has certain engine and inlet restrictions that prevent reducing power to idle thrust at high Mach numbers. The SST may not be faced with such restrictions and may be provided with deceleration devices such as air brakes or in-flight thrust reversers. These will improve the slowdown capability, but the slowdown will still remain a maneuver that requires proper planning and execution.

Landing-Gear Reliability

Experience has shown that the SST landing gear should be relatively simple in design and operation. The landing gear on the number 1 XB-70 has failed to retract or has incurred malfunctions that prevented retraction on 7 of the 78 flights. The number 2 XB-70 had a similar record of malfunctions. There have been flights on which the landing gear did not retract completely on the first attempt, but on one or more subsequent attempts it did lock up and allow the flight to continue as planned. There have been slower-than-normal retraction cycles and there have been cases where usage of the emergency landing-gear extension system was required in order to get the landing gear "down and locked." Since the time of the early XB-70 flights, there have been special emergency switches installed to allow bypassing certain protective relays, and a special hydraulic system has been added to provide redundancy to the nose-gear extension system. The XB-70 cannot be landed without probable catastrophic failure if the nose gear fails to extend; therefore, bailout would be required. Obviously, bailout is not the solution to a serious SST landing-gear malfunction. If possible, the retraction system should use simple mechanical linkages and avoid large numbers of sequence valves and micro-switches that can get out of adjustment and prevent retraction. An even more important requirement is to have a reliable landing-gear extension system. The emergency extension system should utilize the "free fall" method, since even dual hydraulic systems can fail and cause landing-gear problems, as when both XB-70 utility systems failed (fig. 9) and a "tiptoe" landing resulted. The emergency system should also have a pneumatic or hydraulic backup capability and be one in which crew members have high confidence.

Hydraulic-System Operation

There have been numerous hydraulic-system leaks or failures during the test program. Initially there were hydraulic pressure gages but no hydraulic quantity gages in the cockpit. There was strong pilot insistence on the quantity gages, and they were installed before the first flight. They have proved invaluable by providing cockpit knowledge of hydraulic leaks or fluid transfer between hydraulic systems. After several leaks were experienced, a 30-gallon hydraulic reservoir, an electric pump, and a hydraulic replenishing system were installed to allow in-flight reservicing of a low hydraulic system. The system has been used several times to prevent depletion of a hydraulic system and the resulting cavitation of the hydraulic pump and contamination of the hydraulic system. It also reduces the need for an emergency landing. The system was paid for on its first usage, since the cost of overhauling the hydraulic pumps in a failed system is approximately equal to the cost of installing the replenishing system. The present hydraulic panel is shown in figure 10. The SST should have hydraulic quantity gages and some type of replenishing system in addition to the normal pressure gages.

Approach and Landing

The XB-70 is not a difficult airplane to land under the ideal circumstances provided at Edwards Air Force Base. It has excellent speed stability on the final approach and has a very strong ground cushion. The speed stability and the rapid engine response provided through the electric throttle system allows airspeed to be held easily within 2 knots of aim speed. It can be and has been landed from a 3° approach path but is more comfortable when flown on a 1.5° to 2.0° slope. The normal light-gross-weight approach speed of approximately 200 knots is much too high for an SST and causes some apprehension when maneuvering from an offset approach to line up with the runway. Judgment of flare and touchdown altitude is more difficult because of the pilot's height above the ground and because of the high approach speed. The lower the approach and landing speed of the SST, the easier will be the landing task. The XB-70 responds adversely to turbulence, and the pilot's workload increases significantly when landing under turbulent conditions.

CONCLUDING REMARKS

The North American Rockwell XB-70 is a very valuable research vehicle that has allowed important data to be gathered by NASA and the U. S. Air Force that are particularly applicable to the SST program. Its combination of high speed and large size is unmatched anywhere in the world. The extremely reliable J-93 General Electric engines, although never previously flown, have been a strong factor in the success of the program.

The items covered in this paper represent only a small part of the knowledge gained from the test program. Many reports have already been published on the program and NASA has other reports being prepared for publication. The Boeing Airplane Company and the Federal Aviation Agency have worked closely with the XB-70 test team throughout the program and have full access to all XB-70 data.

XB-70A WITH WING TIPS AT 65°

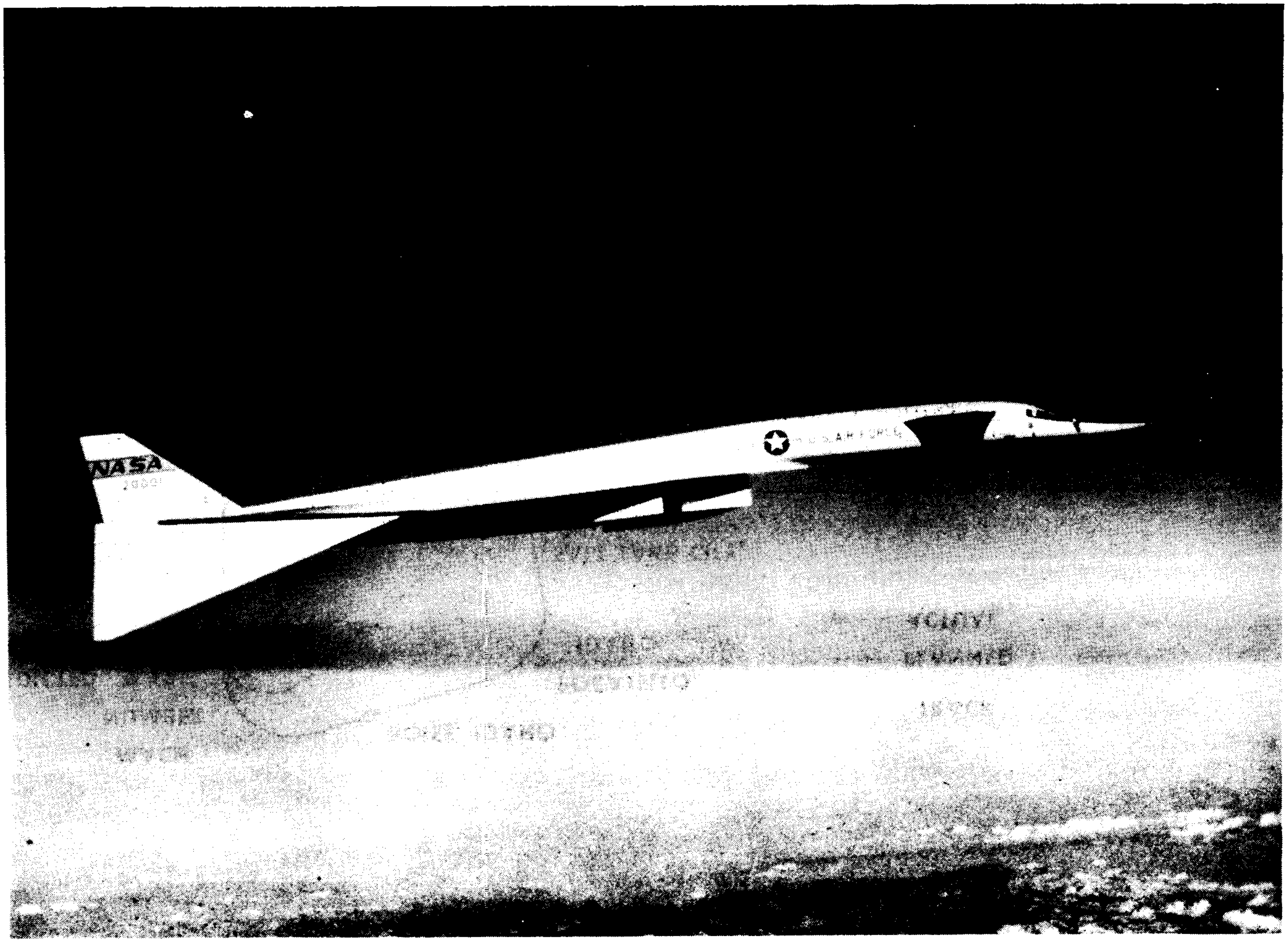
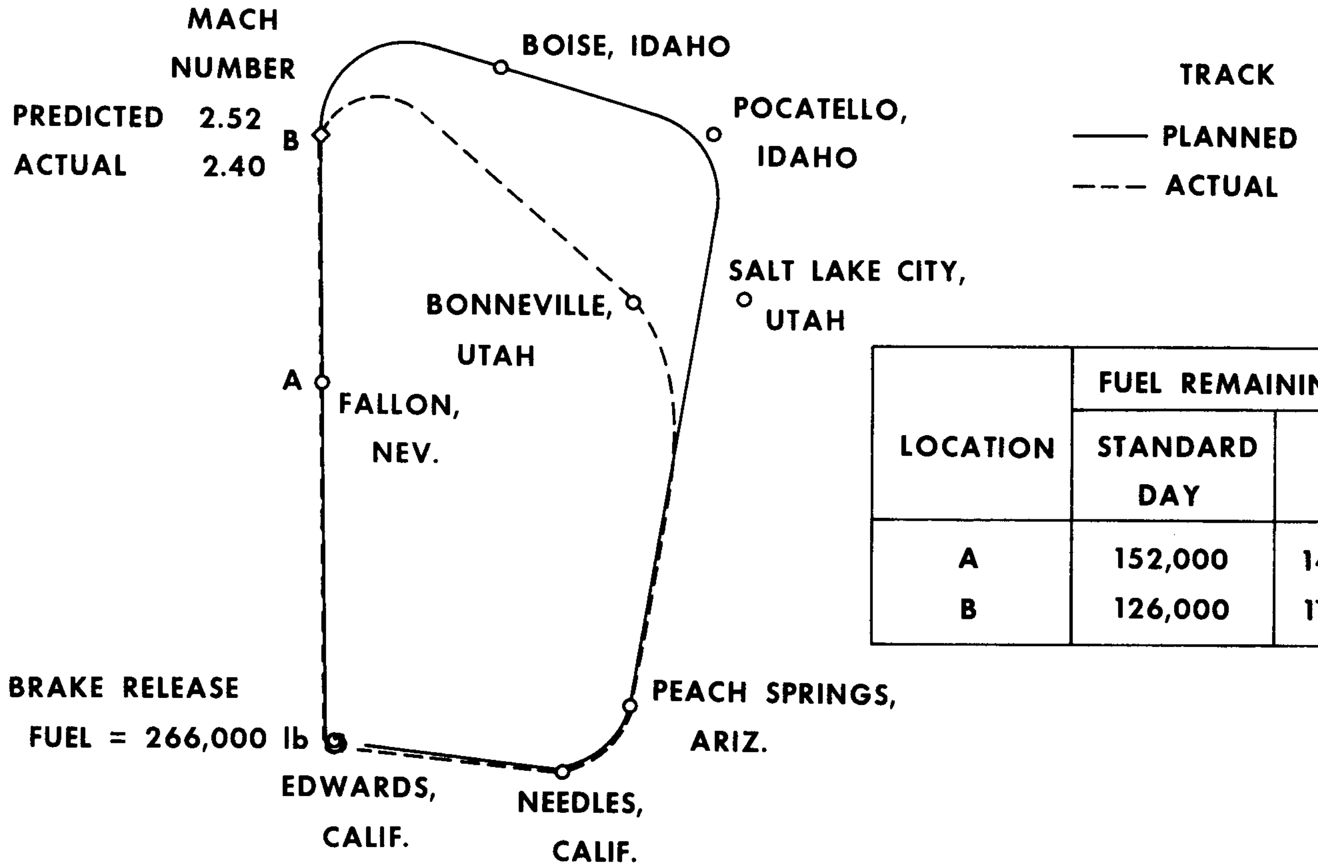


Figure 1

FUEL USAGE

STANDARD DAY VERSUS HOT DAY

ES 3416



LOCATION	FUEL REMAINING, lb		DISTANCE FROM TAKEOFF, n. mi.
	STANDARD DAY	TEST DAY	
A	152,000	147,000	295
B	126,000	112,000	490

Figure 2

WINDSHIELD AND NOSE RAMP

ES 3418

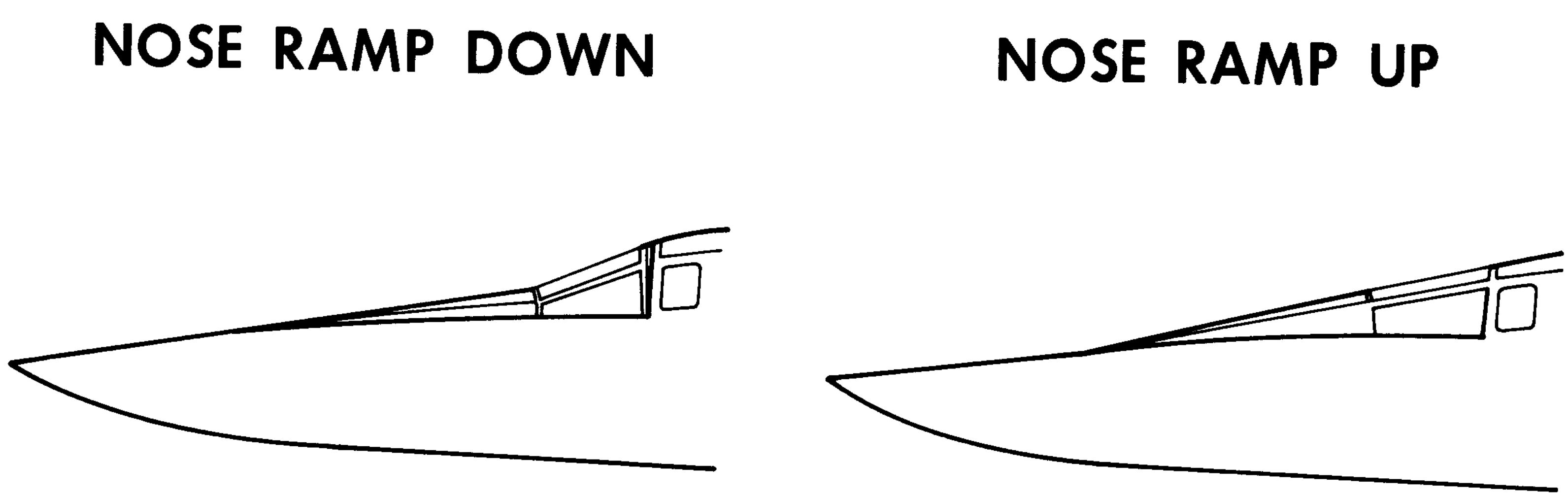


Figure 3

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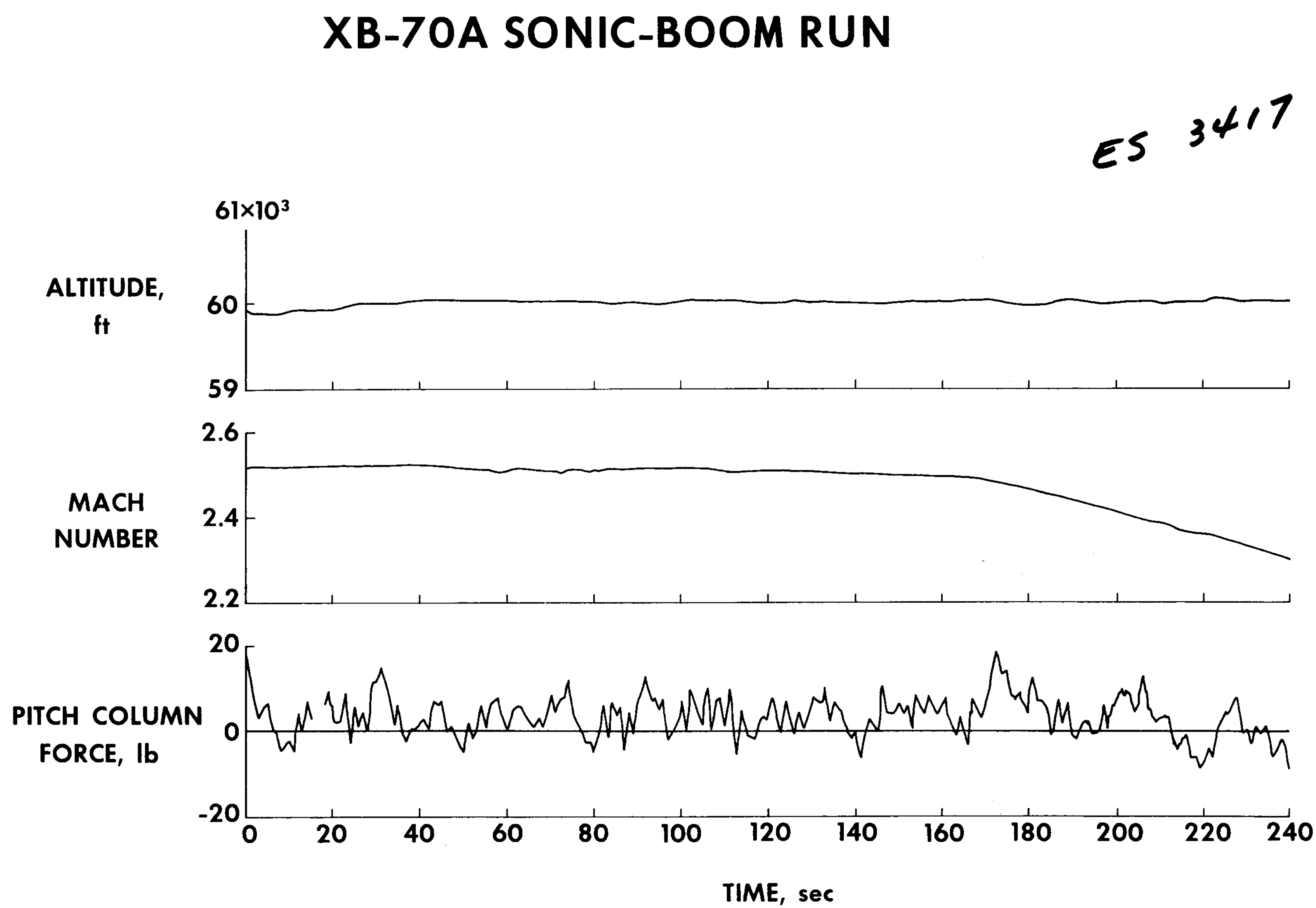

Figure 4

SENSITIVE ATTITUDE DIRECTOR INDICATOR

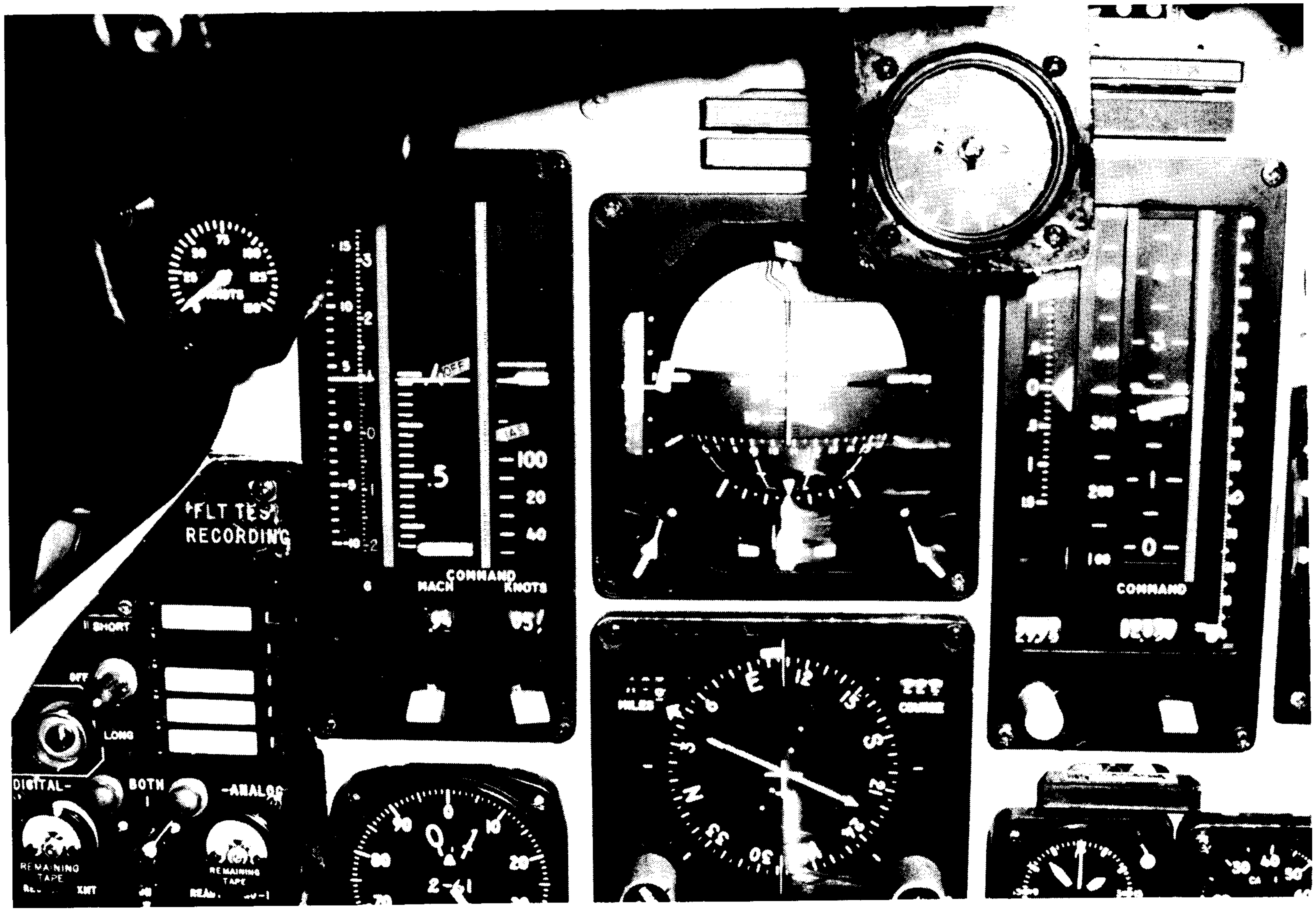

Figure 5

SENSITIVITY SELECTOR FOR ATTITUDE DIRECTOR INDICATOR

Figure 6

NORMAL INLET CONTROLS

LOCATED BETWEEN COPILOT'S LEGS

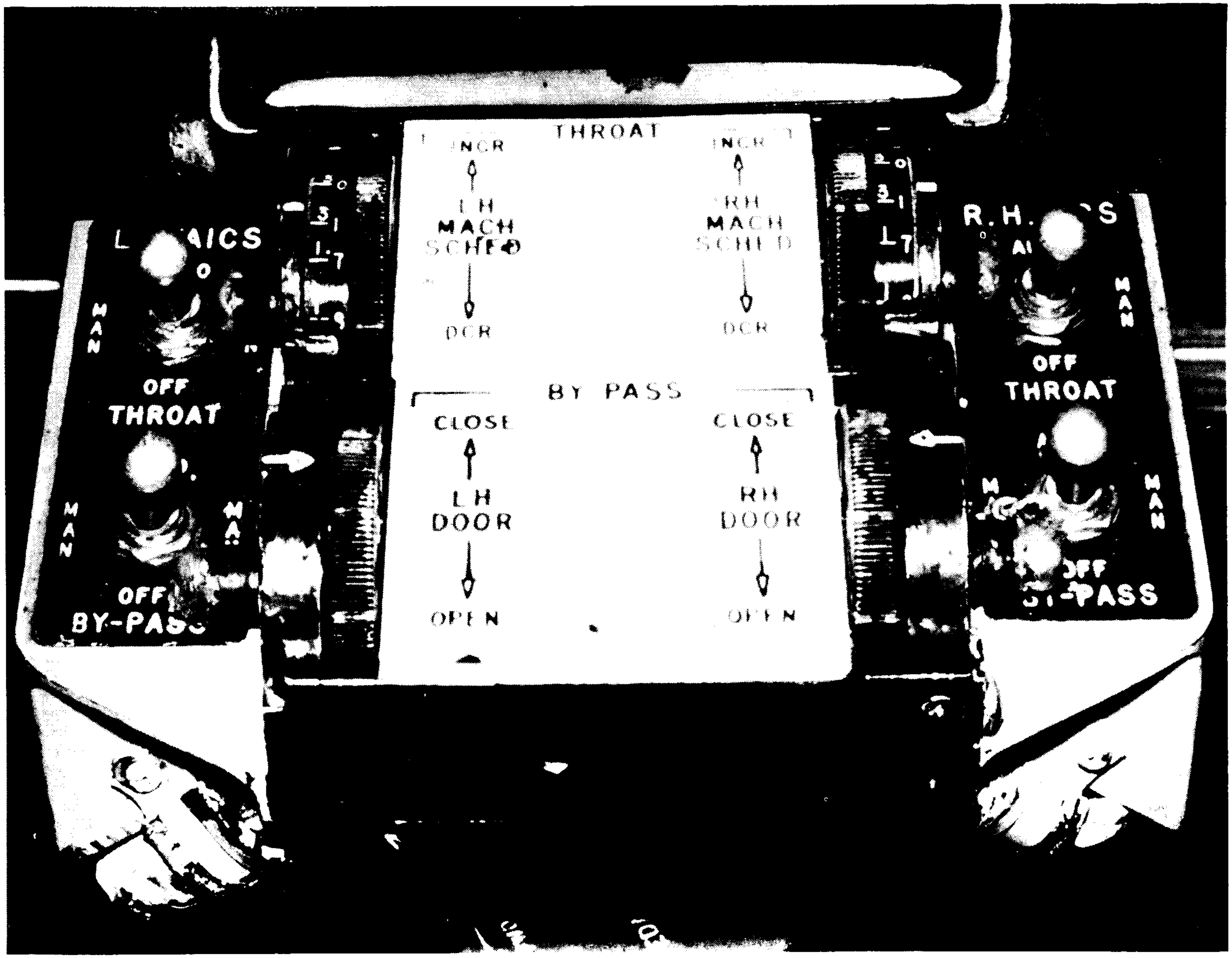

Figure 7

NORMAL INLET INDICATORS AND EMERGENCY INLET SWITCHES

Figure 8

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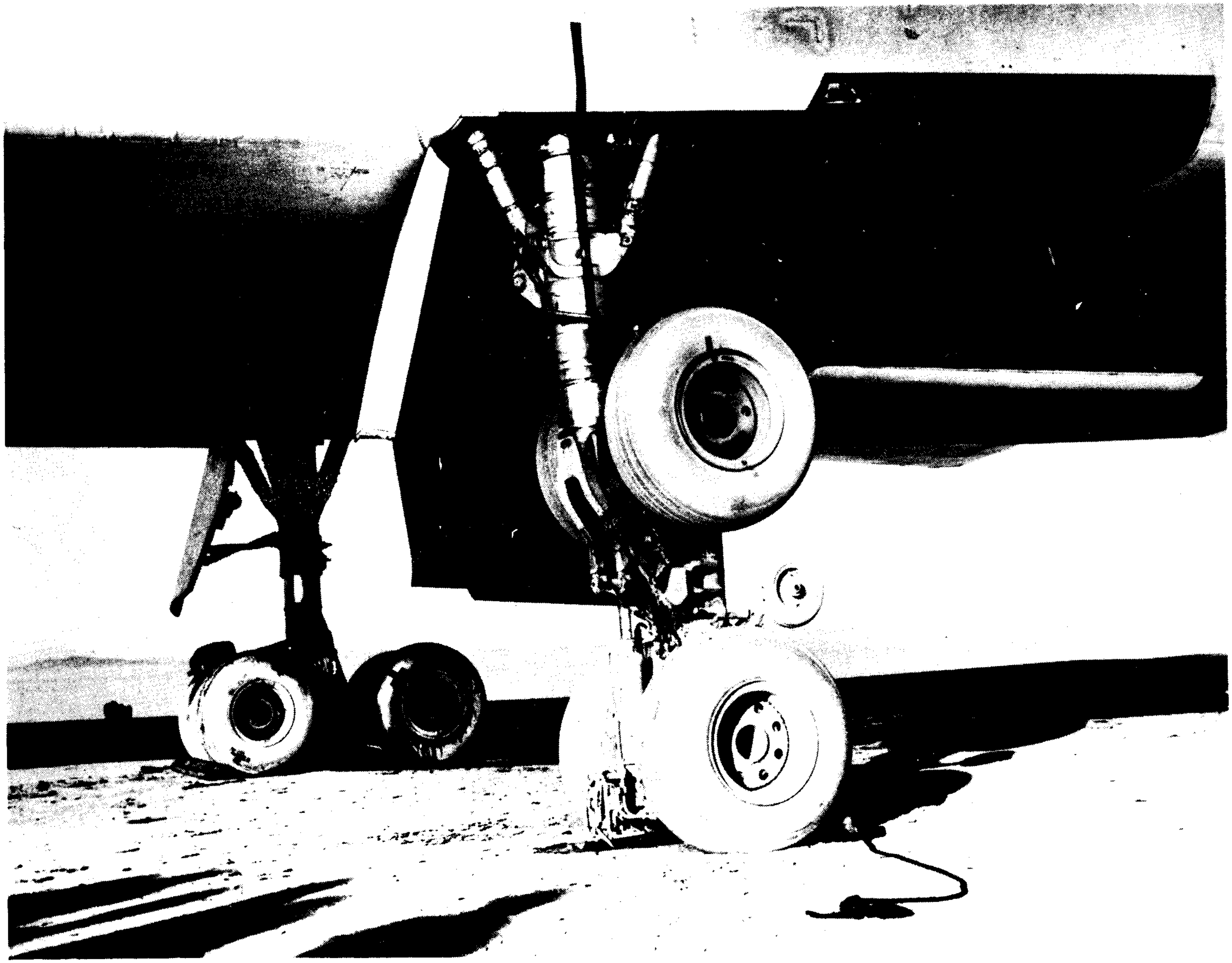
(no title)

EMERGENCY "TIPTOE" LANDING



Figure

HYDRAULIC GAGES AND REPLENISHING SELECTOR

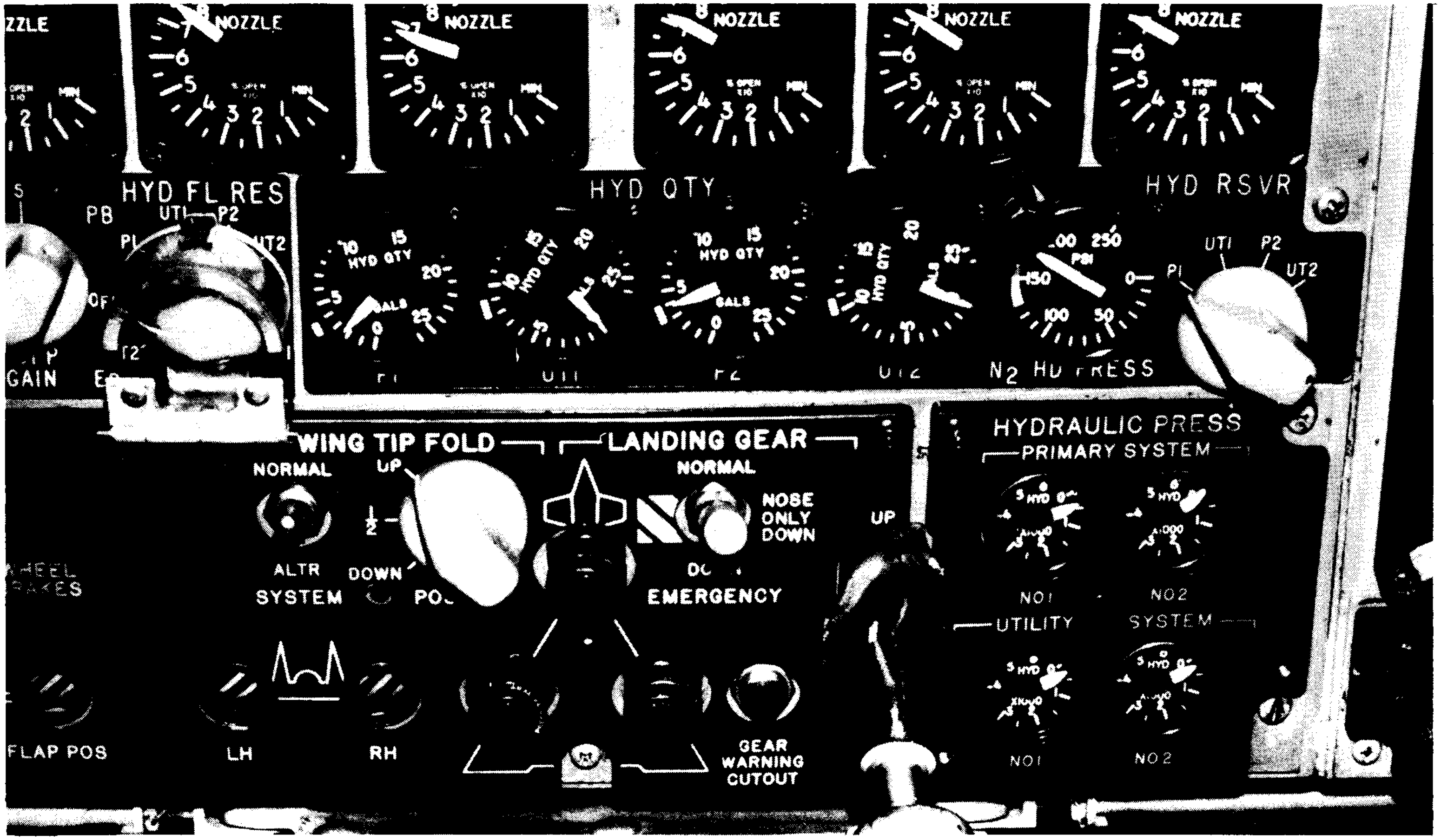


Figure 10